Modelling with a CFD code the near-range dispersion of particles unexpectedly released from a nuclear power plant

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Abstract

An event in November 2007 in Ascó-1 nuclear power plant (Spain) originated the release of a significant amount of hot metallic particles through the discharge stack. Particles were dispersed and deposited in roofs and neighbouring areas within the NPP controlled area. However, the event was not detected until March 2008. More than 1,300 hot points with radioactive particles were found, 94% located inside the double fenced controlled area and 6% within the exclusion area; 5 particles were out of the exclusion area, across the river.

To provide additional insights on the potential consequences of the release, a computational fluid dynamics (CFD) code, Ansys-CFX-11, has been used to simulate the near-range atmospheric dispersion and deposition of the particles. The purpose of the analysis was to assess the distance travelled by particles of different sizes. A very detailed model of the site was built, taking into account the buildings and the terrain features including the river valley and the surrounding hills. The modelled domain was 3.2 x 5.2 km, with the atmospheric layer up to 4 km height. The atmospheric conditions recorded during different periods of time were classified into 37 representative categories.

In general, the distribution of the particles found was adequately reproduced. Particles larger than 100 microns could not travel beyond the double fence. Particles between 50 and 100 microns could have been deposited mainly within the exclusion area, with a small probability of travelling farther. Smaller particles could have travelled beyond, but also should have been deposited in the nearby area, while the majority of particles found are larger, thus indicating that the size of the released particles should be above 50 microns.

The detailed CFD simulation allowed answering relevant questions concerning the possibility of having an impacted region larger than the exclusion area.

Introduction

An incident classified as level 2 on the INES scale happened at the Ascó I nuclear power plant in Spain, consisting of the release of radioactive particles with activated corrosion product isotopes. This occurred due to the contamination of the fuel building ventilation system with water originating from the cleaning of the fuel transfer canal at the end of the refueling outage of the reactor, as a result of a combination of incorrect practices and noncompliance with the operating standards (CSN, 2009a).

The detection of the release and its subsequent notification took place over four months after the occurrence of the event, since it became evident not because of the available automatic radiological control systems but through a site radiological surveillance walkthrough. This was due mainly to the fact that these systems are designed to detect homogeneous radioactive emissions and not discrete particles such as those involved in the event. On March 14th 2008, hot particles were first detected in the containment hatch area. A further increase in radiological surveillance activities in the following days lead to discover several hot points on the roofs of the buildings adjacent to the NPP stack (see figure 1). On April 4th a report was released to the regulatory authority, the Nuclear Safety Council (CSN), which was followed by press releases and official statements to the public, as well as a wide campaign to check more than 2,700 persons through the whole body radiological counter, including workers and visitors. No person was found contaminated. A team of experts from the European Commission's General Directorate of Energy and Transport visited Ascó on April 29th and verified the radiological protection control methodology which confirmed the non-radiological significance of the event and endorsed the technology employed to guarantee the control measures from the operative, administrative and quality points of view.

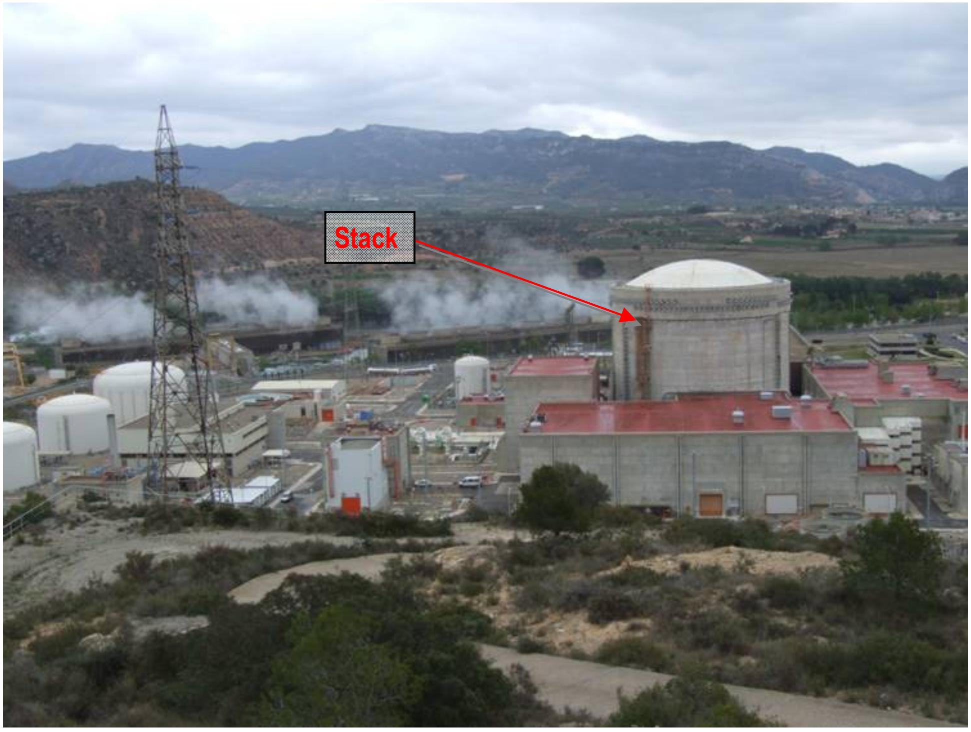

Fig. 1. Photograph of the Ascó I reactor building and the adjacent buildings of the nuclear power plant. The release of particles took place through the stack.

The event was investigated and the conclusion was that the release of hot particles to the atmosphere started on November 29th 2007, when the ventilation system was switched from filtered mode to normal mode (without filtration). As a consequence, particles were dragged out through the stack and then dispersed via the stack to the roofs of Unit I buildings.

An exhaustive active particle location programme was soon accomplished on the plant site, by the licensee in the area under its control and by the CSN in off-site areas, with more than 1,300 particles collected with a total activity of 409 MBq, subsequently calculated on November 26th 2007 (CSN, 2009b). As a comparison, the cleaning of the ventilation system allowed to recover a total of 37,6 GBq. 94% of the particles were located inside the double fenced controlled area and 6% within the exclusion area; 5 particles were out of the exclusion area, across the river (figure 2).

To provide additional insights on the potential consequences of the release, a computational fluid dynamics (CFD) code, Ansys-CFX-11, has been used to simulate the near-range atmospheric dispersion and deposition of the particles. The purpose of the analysis was to assess the distance travelled by particles of different sizes (and activities) and the probability that they have been deposited at a given location.

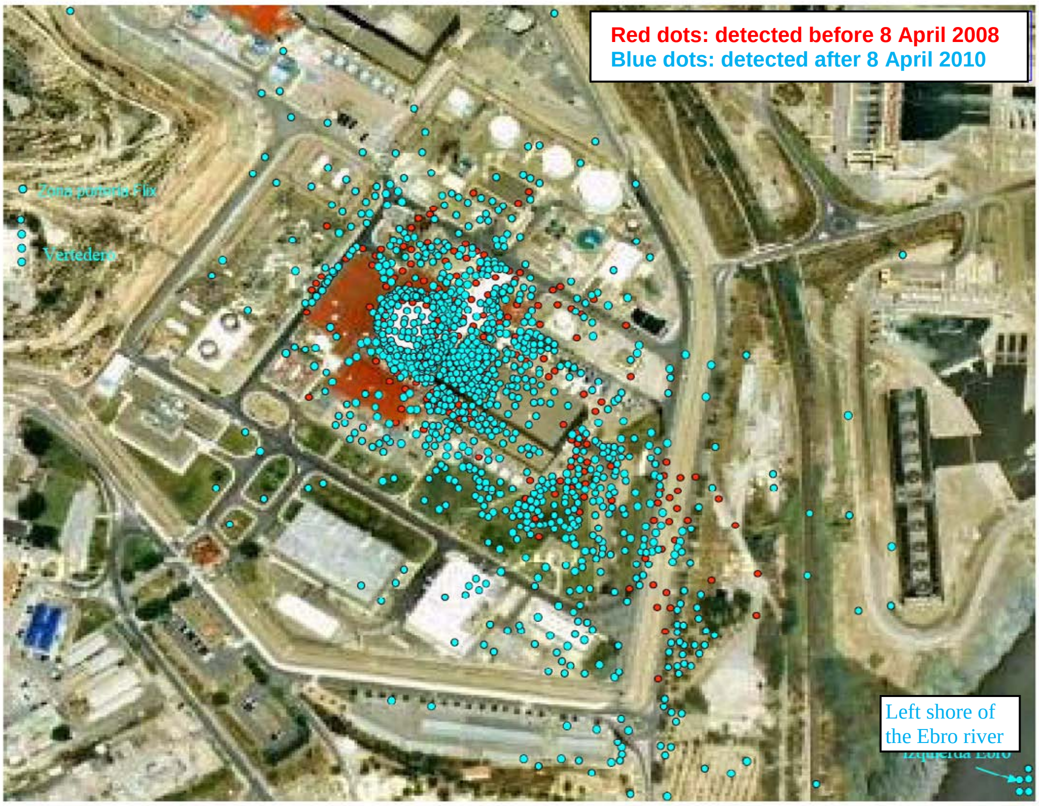

Fig. 2. Aerial view of Ascó I site showing the locations where hot particles were collected.

Material and methods

The modelled fluid flow presents two well differenced phases: a continuous phase of air mixed with steam and a dispersed phase, constituted by solid particles. Consideration of steam was necessary due to the presence of the forced and natural flow cooling towers.

Turbulent phenomena in the air flow have been included in the simulation by means of the SST model (Shear Stress Transport), widely used for industrial applications where limit layer effects in contact with surfaces are relevant. Therefore, the flow characterization is performed by solving the three equations of momentum for gases in x, y and z; the continuity or mass conservation equation; the energy conservation equation; the two equations of the turbulence model: for turbulent kinetic energy and frequency of turbulent structures; and the transport equations for steam. Also, the equations relative to particle transport which are solved by means of a lagrangian model coupled to the fluid flow model (one-way coupling).

A very detailed numerical model of the site was built, taking into account the buildings and the terrain features including the river valley and the surrounding hills. The modelled domain was 3.2 x 5.2 km, with the atmospheric layer up to 4 km height. The atmospheric conditions recorded during different periods of time were classified into 37 representative categories.

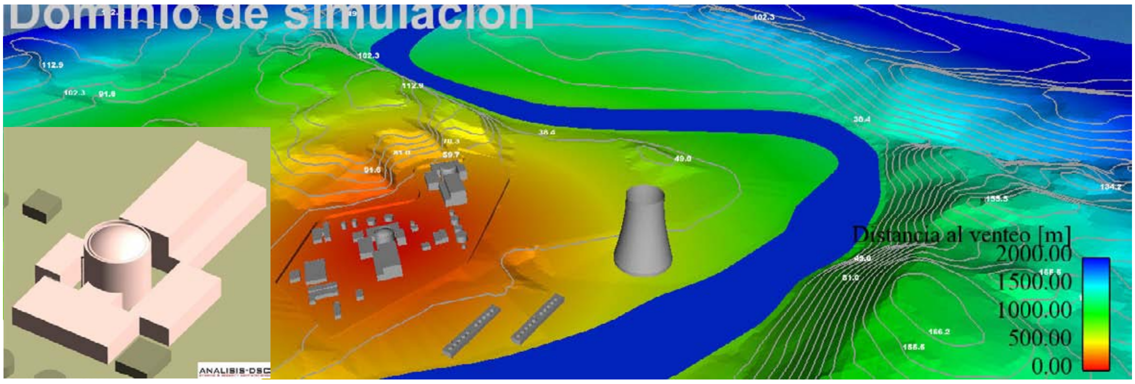

Fig. 3. Overall view of the geometric model of Ascó I site. On the left, a detail of the main buildings of the plant.

The steps followed in the study were the following:

1. Generation and adjustment of a 3-D detailed model for Ansys-CFX based on the terrain elevation (digital map of the area) and the dimensions of the buildings. The building geometries are less detailed for those that are farther from the release point. The general view of the geometric model can be seen in figure 3. The nodalization and mesh structure of the model is based in tetrahedrical finite volumes complemented by prismatic volumes near the surfaces. It is shown with some details in figure 4. Near the surfaces, the size of the cells is small enough as to adequately capture the behaviour in the interface.
2. Analysis of the meteorological data recorded at the site between 29 November 2007 and 31 January 2008. Data have been recorded at 10, 24.5 and 60 m above ground at 15 minutes intervals. The analysis of these data has lead to classify the different atmospheric conditions in a total of 37 categories as reasonably representative of the local meteorology during the period under study. There was a compromise between the need for realistic calculations and the computational resources needed for each simulation. In practical terms, the combination of these 37 categories, with adjusted frequencies, allowed to reasonably represent the atmospheric conditions in the following periods: 29/Nov/2007; from 29/Nov/2007

to 31/Dec/2007; from 29/Nov/2007 to 31/Jan/2008 (one day, one month and two months from the change in the ventilation system to non-filtered mode).

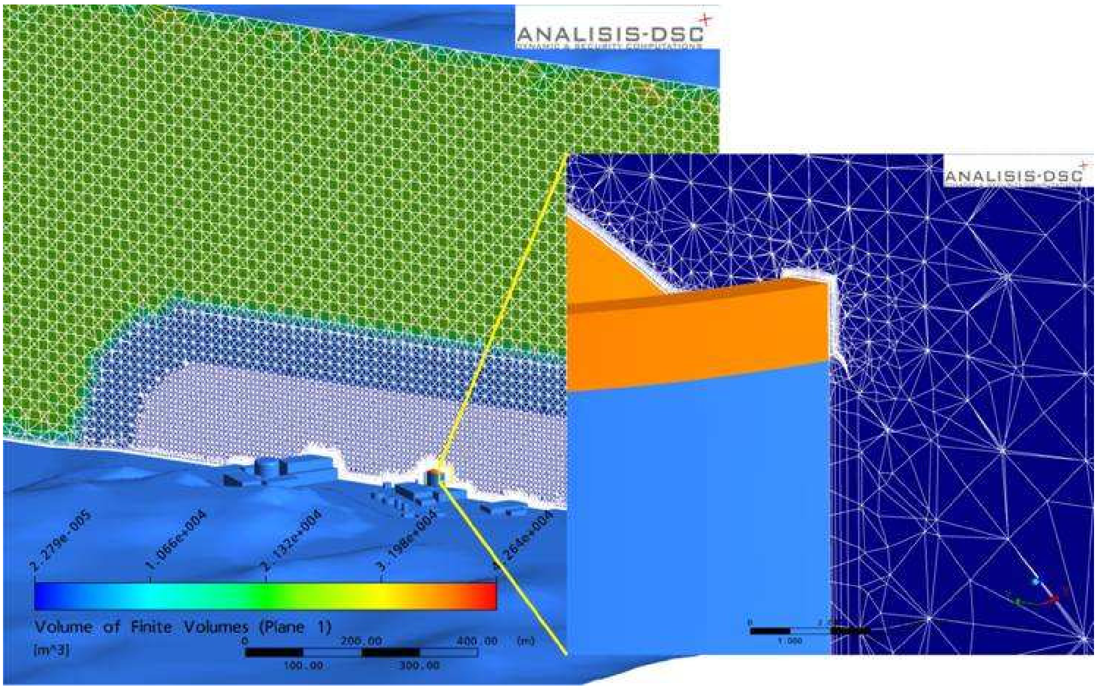

Fig. 4. Details of the nodalization of the atmosphere around the reactor building and in the mid-range distances along the site and up in the atmosphere.

3. Simulation of the 37 categories, with specific conditions of temperature gradient and atmospheric stability, relative humidity, wind speed and direction. The temperature gradient chosen was the typical for the atmospheric stability (Snell, 1994) and the most frequent temperature was chosen as representative for each category. Wind speed profiles with height were adjusted by considering a potential law dependent on the atmospheric stability (Hanna, 1982). The air flow released from the stack is 37 m^3/s with a temperature 20ºC. 3-D effects in the air flow around the site were very relevant, due to the irregular terrain features and the influence of the cooling towers.
4. Seven classes of particles were taken into account in the simulations: 1–25 μm; 25–50 μm; 50–75 μm; 75–100 μm; 100–150 μm; 150–250 μm; 1–250 μm. For bigger sizes, their behaviour is dominated by inertial forces and their distribution is similar. Larger particles could not leave the stack, as demonstrated with a preliminary study of balance of forces in the released flow. The particles density was taken as 7 g/cm^3, as it corresponds to metallic compounds from corrosion of the reactor primary cooling circuit.
5. Parametric study to get a probability of deposition of particles of different size in a given zone, taking into account the atmospheric dispersion. Combination of results for each of the 37 categories with their frequencies during each time period.

Results

The particle deposition map (fig. 2) is the result of the atmospheric dispersion and deposition of the particles released through the stack plus the later processes of resuspension and deposition by wind, transport by rain water runoff and other weathering factors which cannot be simulated in the model. It is therefore reasonable to see some differences with respect to the calculated deposition patterns. It is also necessary to remind that the collection of particles started in April 2008, while the release took place from 29 November 2007.

In order to give a useful representation of the deposition pattern, the number of simulated particles was 10,000 for each size range of 25 microns. To represent it, we have multiplied it by 100 so we have a number of 10^6 particles and the graphical representation displays the number of particles deposited (per m^2) per million particles released. The minimum representation limit is 1 particle per m^2. For the global case comprising 1–250 µm the number of particles assumed was 10^7.

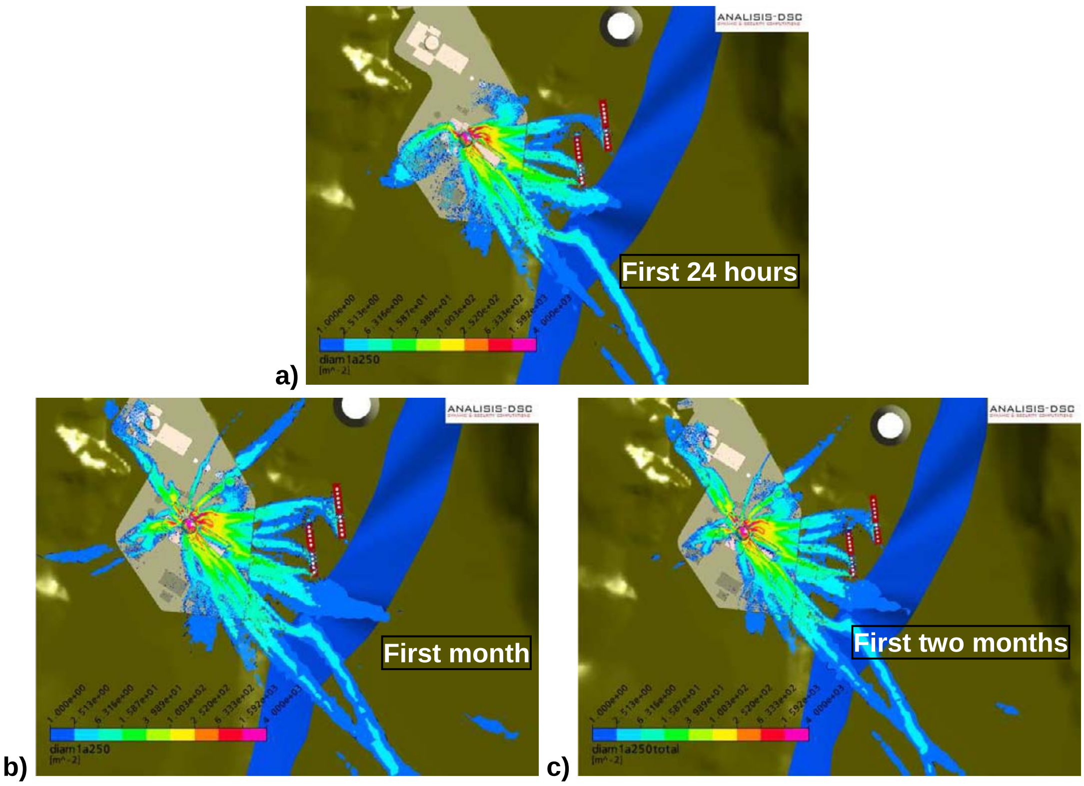

Fig. 5. Results of the simulated deposition of particles of diameters 1–250 µm considering the atmospheric conditions in three different time periods. The patterns represent the particle density per m^2 assuming a release of 10^7 particles.

There is a preferential deposition in the South East area, partly due to the higher frequency of winds in that direction, combined with the effect of the forced flow cooling towers which force humid air to go upwards and which cause some entrainment of particles in that direction. By comparing the three periods considered in the calculations, the conclusion is that a release during the first 24 hours (fig. 5-a) cannot explain alone the pattern of particles found. However, the deposition reached in the period from 29 November 2007 to 31 December 2007 (fig. 5-b) is very similar to the one if the period extended up to 31 January 2008 is considered (fig. 5-c). This result suggests that the release could have taken place most likely in the first month after the change of the ventilation system to normal mode.

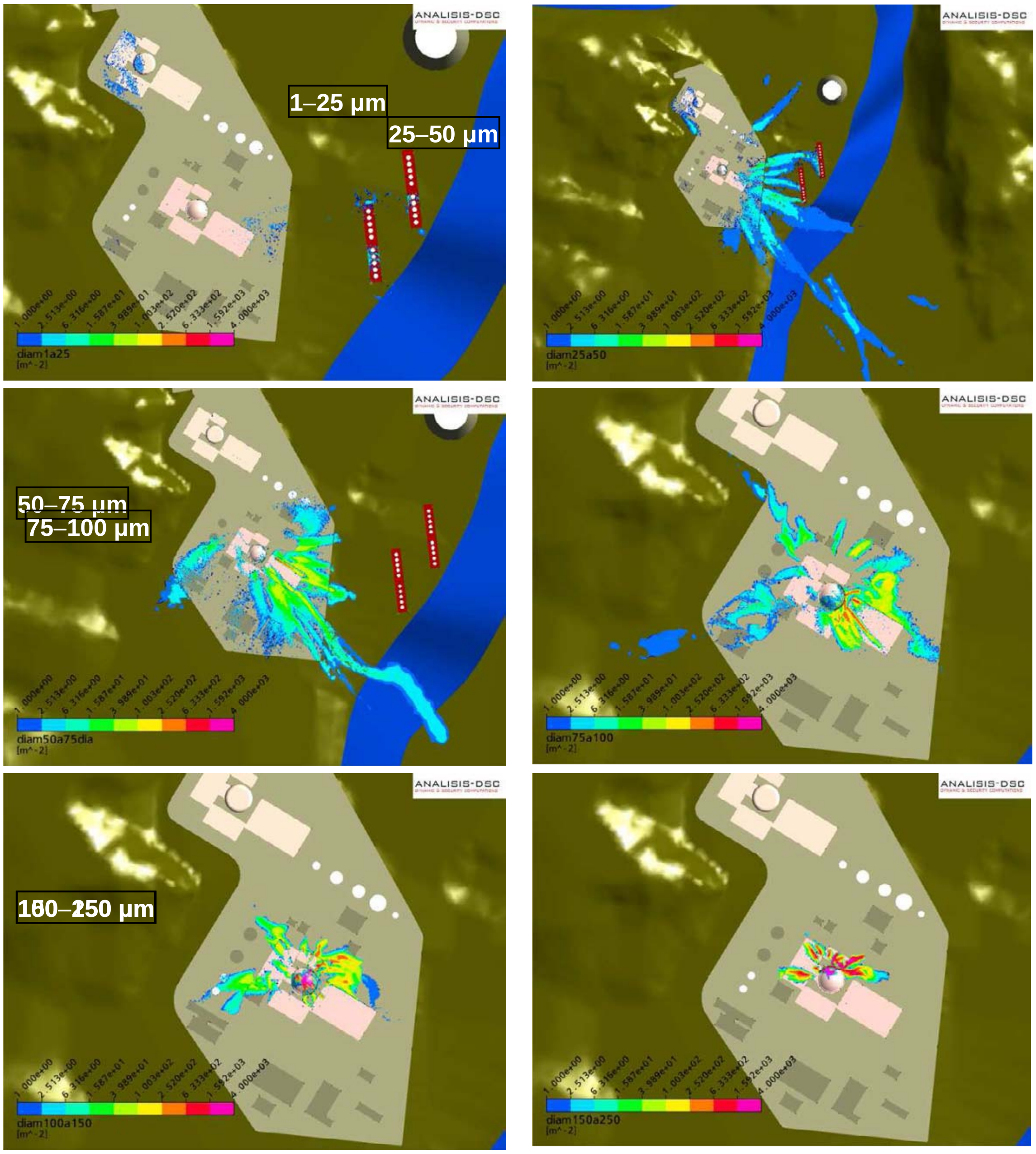

Fig. 6. Results of the simulated deposition of particles of different diameter ranges considering the weather conditions during the first month after the change of the ventilation system to normal mode (29/Nov/2007 to 31/Dec/2007). The patterns represent the particle density per m^2 assuming a release of 10^6 particles.

Fig. 6 displays the deposition patterns of particles of different size. Small particles (1–25 µm), of very low activity compared to the large ones, would be able to travel out of the calculation domain. They could also deposit, in small concentrations, around the stack and in other points of the site, with influence of the forced flow cooling towers.

However, in the radiological survey such small particles were not found, and therefore this result suggests that, if present, their fraction in the total should have been extremely low.

Particles of larger size (25–50 μm) show a distribution through a very large area, and their deposition density should be very small, with a likely deposition within the site, but also off-site. A significant fraction of such particles is leaving the calculation domain.

For particles with size between 50–75 μm, the larger fraction should be deposited within the site, although some of them could travel a bit out and cross the river. This could explain why 5 particles were found in that zone after a careful radiological survey. The radial-like deposition pattern seen in the figure is a reflection of the way in which the calculation has considered wind directions, with fixed angle in each category and a weighted combination of the results obtained.

When larger particles are considered, with sizes between 75–100 μm, they hardly seem able to leave the site, and they are deposited mainly along the dominant wind directions, towards E and SE as commented above.

Particles with size between 100–150 μm would be totally deposited within the plant fence, dominantly towards E and NE, because of the influence of the buildings in the local wind flow patterns. The majority of particles found did have sizes of this range, which could have been altered with time due to the particle "life" in the environment. In fact, many particles show a composition which is not purely metallic but associated with carbonates or silicates.

The biggest particles, with diameter larger than 150 μm, relatively very heavy and active, would deposit totally in short distances around the stack, many of them in the roofs of the reactor building and the surrounding buildings: auxiliary equipment building; fuel management and storage building; turbine building. Some of them would be trapped by the main wind flow and be able to go beyond the buildings, but certainly not far from the plant due to their high inertia. Later, resuspension or runoff phenomena could have transported them farther.

Discussion

This study had as starting point the distribution of the deposited particles, after about four months of weathering in the site. However, it has been affected by some uncertainties impossible to exclude; two of them were fundamental:

- Knowledge of the precise moments at which the release of particles took place.
- The particle size.

The study has tried to overcome these uncertainties by undertaking a wide parametric study covering a full range of particle sizes, from very small to the largest particles able to exit through the stack at the existing flow dynamic conditions, together with a variety of atmospheric conditions, 37 in total, which covered a high percentage of those existing during the likely emission periods.

Based on those considerations, the study has given valuable information with regard to the likely deposition pattern of particles of different sizes in different release periods, concluding that particles of all sizes could have been found within the inspected area where the hot particles were found. Particles larger than 100 μm could have not travel beyond the fenced area of the plant. A small fraction of particles sized between 50–75 μm could have leave the fenced area travelling towards the SE direction, where some particles were effectively found across the river. Small particles could in principle have travel far from the site, but they should also have deposited on site, and this was not the actual finding. Given their origin and the spread of particles found it is not very likely that these small particles were abundant in the release.

Conclusions

The main conclusion is about the usefulness of this study in order to better assess the radiological importance of the event. The great capability of CFD models to simulate very local effects –like the flow perturbation by the forced cooling towers, the buildings of the plant or the surrounding hills–, has proven essential to accurately interpret the behaviour of particles of different sizes. In summary, the detailed CFD simulations allowed answering relevant questions concerning the possibility of having an impacted region larger than the nuclear power plant exclusion area.

However, to give realistic results, these models need a significant effort in terms of modelling the site features, terrain elevation and geometry of the buildings and installations which could alter the overall wind flow. Also, current computational capacities in general do not allow simulating dynamic sequences with changing weather; therefore, we have chosen a representative set of "static" sequences and have weighted the results in order to obtain a realistic pattern of the likely deposition of the leaked particles.

In general these methods would be recommended only when the geometry and dispersion conditions of the site are very complex as well as in the case of particles whose dispersion is better simulated with lagrangian models.

Acknowledgements

We deeply acknowledge the support received from "Asociación Nuclear Ascó-Vandellós II", and their supply of data for the simulations.

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